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Published in:
28th European Conference on Optical Communication, 2002. ECOC 2002.

Link to article, DOI:
[10.1109/ECOC.2002.204430](https://doi.org/10.1109/ECOC.2002.204430)

Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Riishede, J., Hougaard, K. G., Libori, S. E. B., Søndergaard, T., & Bjarklev, A. O. (2002). Bragg gratings in index-guiding photonic crystal fibres. In *28th European Conference on Optical Communication, 2002. ECOC 2002*. (Vol. 2, pp. 1-2). IEEE. <https://doi.org/10.1109/ECOC.2002.204430>

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Bragg Gratings in Index-guiding Photonic Crystal Fibres

Jesper Riishede, Kristian G. Hougaard, Stig E Barkou Libori, Thomas Søndergaard* and Anders Bjarklev

Research Center COM, Technical University of Denmark, Building 345V, 2800 Kgs. Lyngby, Denmark

*Micro Managed Photons A/S, COM, Building 345V, DTU, 2800 Kgs. Lyngby, Denmark

Tel: (+45) 4525 3810, Fax: (+45) 4593 6581, E-mail: riishede@com.dtu.dk

Abstract A numerical investigation of coupling coefficients of Bragg-gratings in index-guiding photonic crystal fibres is presented. It is shown that index-guiding photonic crystal fibres have larger coupling coefficients for fibres with small core areas than step-index fibres.

Introduction

In recent years, photonic crystal fibres (PCFs) have attracted a considerable amount of attention. PCFs are typically made from undoped silica and their waveguiding properties are provided by an array of air holes distributed over the cross-section of the fibre¹. Conventionally, PCFs are divided into two fundamentally different kinds of fibres. The first kind, the index-guiding PCFs, operate by a principle similar to total-internal reflection, while the second kind uses the so-called photonic bandgap effect to guide light in a low index core-region².

The index-guiding crystal fibre is the most studied kind of PCF, and it is known to possess some unique properties, for instance the ability of guiding only one mode at all wavelengths³. The fabrication technology of PCFs has matured significantly over the last years and today focus has shifted towards applications of the fibres rather than studying their guiding mechanisms. The combination of PCF and Bragg-grating technology represents a research area that is expected to hold a wide range of applications. So far, the modelling issue of Bragg-gratings in PCFs has only been slightly addressed, and the results have been based on a beam propagation method (BPM)⁴ that it not able to accurately model PCFs with large air filling fractions.

In this paper, we present a numerical method based on a full-vectorial mode solver. The method is used to investigate the coupling coefficient of different index-guiding PCFs and the results are compared to a step-index fibre.

Numerical Model

Figure 1 shows an example of the geometry of an index-guiding PCF with a cladding region made from a triangular air hole lattice. The waveguide core of the fibre has been created by omitting an air hole in the centre of the structure. The PCF is uniquely defined by the hole spacing, Λ , and the hole diameter, d . In order to calculate the field-distributions and mode indices of the fibre, a full-vectorial planewave method, that accurately takes the complex topology and the

large index contrast of the fibre into account has been applied to the waveguide geometry.

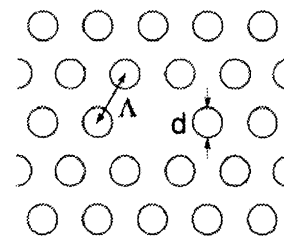


Figure 1: Structure of the index-guiding photonic crystal fibre.

The Bragg-grating written in the core region of the fibre is considered to be a perturbation of the ideal waveguide. Therefore, the field distributions of the unperturbed waveguide can be used to calculate the coupling coefficients, derived from coupled mode theory, that is used to describe the coupling interaction of the grating. In the case of coupling between a forward and backward propagating core mode, the coupling coefficient is given by⁶:

$$\kappa_r(z) = \frac{\omega \epsilon_0 n_{co}^2 \sigma(z)}{2} \int_{UV} (|E_x|^2 + |E_y|^2) dA \quad (1)$$

Here, the overlap integral is only made over the UV-sensitive part of the fibre. In accordance with the definition⁶:

$$P = \frac{1}{2} \text{Re} \int_{\infty} (E_x H_y^* - H_x E_y^*) dA = 1W \quad (2)$$

the fields inserted into equation 1 have been normalized to carry 1W.

Coupling coefficients in Index-guiding Photonic Crystal Fibres

The endlessly single-mode property of index-guiding PCFs is a consequence of using air holes in a single material background to provide the confinement properties of the waveguide. However, in order to introduce photosensitivity in the fibre, the core region of the PCF has to be doped with germanium. As germanium is known to raise the refractive index of the glass-material, this would alter the waveguiding properties of the PCF - in particular the limits of single

mode operation. In the analysis presented here, it is therefore assumed that the photosensitive glass-material has been co-doped with an index-lowering dopant (such as fluorine) to match the refractive index of pure silica. Also, it is assumed that the central glass tube of the fibre geometry defines the photo-sensitive region of the fibre.

In figure 2 the coupling coefficients calculated at a wavelength of $1.55 \mu\text{m}$ for three different PCFs are mapped out against the hole spacing. The coupling coefficient of a step-index fibre (SIF) with a core-index of 1.458, a cladding index of 1.45 and an increasing core radius has been included in the figure. It is known that in a simple analogy, the index-guiding PCF may be seen as a step-index fibre with a core radius defined as⁷:

$$a_{PCF} = 0.625\Lambda$$

In figure 2, we have reverted this analogy to define equivalent hole spacing for the step-index fibre, in order to make an efficient comparison. The dashed lines in the figure correspond to the regions where the fibres are multimoded.

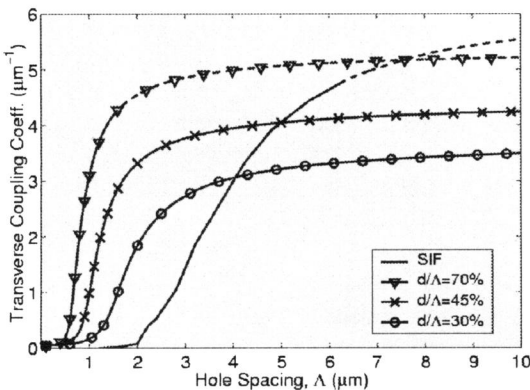


Figure 2: Coupling coefficients for three different PCFs and a step-index fibre calculated at a wavelength of $1.55 \mu\text{m}$

From figure 2 it is seen that for small values of the hole spacing, larger coupling coefficients can be achieved in PCFs than in step-index fibres. This is ultimately due to the large index-contrast between the air holes and the silica-matrix. This result indicates that index-guiding PCFs have an apparent advantage over step-index fibres in applications based on Bragg-gratings written in a fibre with a small core area. Another important result to be seen from figure 2 is that the coupling coefficient of the PCFs increases with the hole spacing and approaches a constant level. The magnitude of this constant level increases with the normalized hole diameter, d/Λ . Furthermore, by comparing the coupling coefficients of the PCFs and the step-index fibre it is seen that the maximum value of the coupling coefficient is largest for the step-

index fibre. These results may be seen as a consequence of the core mode of the PCF being tightly confined to the area within the first row of air holes at large normalized frequencies, Λ/λ . The magnitude of the coupling coefficient is determined by the overlap between the core mode and photo-sensitive region.

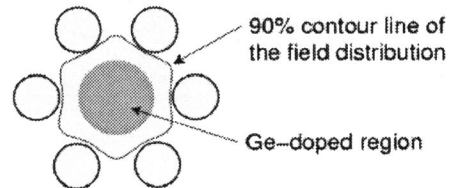


Figure 3: The overlap between the UV-sensitive region and the core mode at a large normalized frequency, Λ/λ .

Figure 3 shows that there is no complete overlap in PCFs, but by increasing the normalized hole diameter a better overlap is achieved. This results in larger coupling coefficients and explains the increased coupling as the hole spacing is increased in figure 2. In the step-index fibre the waveguide core and the photosensitive region are identical, and therefore a much better overlap with the core mode is obtained. Consequently, a larger coupling between counter propagating core modes can be achieved in step-index fibres than in PCFs where the Bragg-grating is written in the central Ge-doped silica tube that has been index matched to pure silica.

Conclusion

We have investigated the coupling coefficients of Bragg-gratings in index-guided photonic crystal fibres. For the simple design investigated, it was found that the coupling coefficients of photonic crystal fibres (PCFs) are generally lower than coupling coefficients of standard step-index fibres. The large index difference between air and silica, however, offers the possibility of much tighter confinement in PCFs, and therefore the possibility of small-core Bragg-grating PCFs.

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